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Heterogeneous crystalline crust controls the shallow thermal field – a case study of Hessen (Germany)

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Abstract

We present a seismic- and 3D-gravity-constrained lithospheric-scale 3D structural model of Hessen that differentiates 7 sedimentary units, 5 Variscan upper crustal bodies, the lower crystalline crust and the lithospheric mantle. To predict the present-day subsurface temperatures, we solve the steady-state conductive heat equation by using a 3D FE method and assigning lithology-dependent thermal properties. We show that the thermal field is mainly controlled by the varying radiogenic heat production in the crystalline crust, which results in a colder NW and a warmer SE domain. Locally, this regional trend is superimposed by thermal blanketing of low-conductive sediments leading to higher temperatures.

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Keywords: Upper Rhine Graben; structural model; gravity modelling; conductive thermal model; Variscan domains

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1. Introduction

Understanding the thermal field is key to assess the huge potential for geothermal energy in sedimentary basins. In general, conductive heat transport is dominant in the crust, controlled by the lithospheric thickness, the radiogenic heat production of the crystalline crust and the thermal conductivity of the sediments [1].

For our study area of the German federal state of Hessen a 3D structural model of the sediments already exists (Hessen3D; [2]), that predicts temperatures by using a combined approach of interpolation of temperature measurements and a correlation of the depth of the Moho with known regional geothermal gradients. As interpolation is not accounting for structural heterogeneities, we evaluate our result of a lithospheric-scale 3D thermal model considering a gravity and seismically constrained structure, reasonable rock properties and the physics of heat conduction.

Whereas the structure of the sediments and sedimentary rocks and the depths of Moho and Lithosphere-Asthenosphere Boundary (LAB) are well constrained, the internal structure of the crystalline crust is poorly known in the study area. Some deep seismic lines show an almost 'transparent' upper and a highly reflective lower crystalline crust (e.g. [3]). As information about the crustal structure is missing between the seismic lines, we want to assess the internal structure of the crystalline crust and its influence on the thermal field using a data-based 3D gravity and 3D thermal modelling approach.

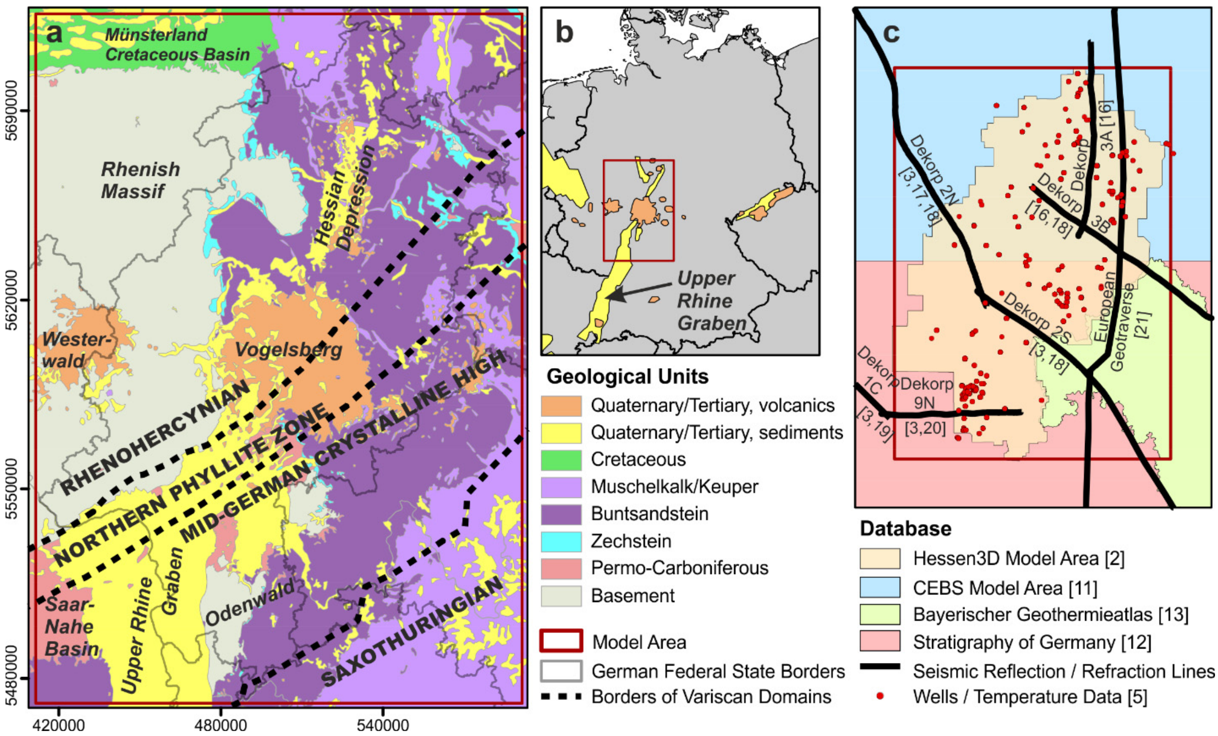

Fig. 1. (a) Geological map (modified after BGR [4]) showing the main geological units of the model area and the Variscan domains (after Bär [5]). (b) Map of Germany with location of the study area and parts of the European Cenozoic Rift System (after Ziegler [6]). (c) Input data for the structural model and location of wells with temperature data used for thermal model validation.

The geological setting of Hessen is mainly characterised by lithologies and structures developed by two tectonic events. In Ordovician to Carboniferous times several terranes collided due to the Variscan Orogeny (e.g. [7]). At the surface the boundaries of these domains can be traced in outcrops [8], that have been used to subdivide the upper crust in the 3D model (Fig. 1a). The NW of the model area is mainly characterised by the low- to medium grade metasediments and metavolcanics of the Rhenohercynian with the outcropping Rhenish Massif. The SE is differentiated into the Northern Phyllite Zone, comprised of medium to high grade metamorphic pelagic to hemipelagic as well as volcaniclastic source rocks [9], the Mid-German Crystalline High with the outcropping mainly felsic granitoids and subsidiary high grade metamorphic rocks and mafic intrusives of the Odenwald [10], and the Saxothuringian. These Variscan domains are overlain by sedimentary successions of different ages. The oldest sedimentary unit can be found in the Permo-Carboniferous Saar-Nahe Basin in the SW. The Quaternary to Tertiary sediments of the Upper Rhine Graben (URG) and the Hessian Depression as well as the volcanics of the Vogelsberg and smaller volcanic structures are the youngest lithologies in the model area and are related to the European Cenozoic Rift System (Fig. 1b). This passive rift system developed in the Eocene due to extension in the foreland of the Alpine Orogen and is still active [6].

2. Database and Methods

2.1. 3D Gravity Modelling

For the construction of the 3D structural model a large data set was used (Fig. 1c). In the sedimentary part, the model is mainly based on Hessen3D, a 3D structural model of the federal state of Hessen based on seismic and well data [2]. Outside the Hessen3D domain information about sedimentary depths were taken from a 3D structural model of the Central European Basin System [11] and published sedimentary depth maps [12, 13]. Furthermore, surface information such as geology [4], topography [14] and magnetic anomalies [15] were taken into account. For the construction of the crystalline crust we used 2D seismic reflection and refraction profiles (Fig. 1c). The seismic reflection lines from the DEKORP project (Deutsches Kontinentales Reflexionsseismisches Programm) were time-migrated, depth-converted and in combination with published interpretations [3, 16-20] used to define an upper and a lower crystalline crust. In addition, seismic velocity information from the refraction seismic line of the European Geotraverse EGT [21] provided indications for reasonable densities after Barton [22] and lithologies following Christensen & Mooney [23] (Tab. 1). The depth of the Moho is based on seismic profiles as well [24] and the depth of the LAB on receiver function analysis [25]. The final 3D structural model has a horizontal extent of 180x255 km and a horizontal resolution of 3 km.

As the few deep seismic lines are not sufficient to assess the internal structure of the crystalline crust below Hessen, we performed 3D gravity modelling by using the software IGMAS+ [26] and the free-air gravity anomaly data of the EGM2008 [27]. For that, each model unit was populated with an appropriate bulk density value (Tab. 1). These values were mainly measured at samples from the study area [5, 28], or derived from velocities of the EGT profile. Although the depth of the top lower crust is mainly based on seismic lines, the interface between both layers was interactively adjusted during the gravity modelling in the regions where seismic information is missing. As a fit with the measured gravity was not possible by adjusting the geometry of the two crustal layers only, a differentiation of 5 bodies in the upper crystalline crust was implemented.

2.2. 3D Thermal Modelling

For the calculation of the present-day 3D conductive thermal field a 3D finite element method was used to solve the conductive heat transport equation for steady-state conditions [29]. For the thermal calculation values of thermal conductivity and radiogenic heat production were assigned to each model unit (Tab. 1). Therefore, we used not only measured rock properties (e.g. [5, 30]), but also new insights from the 3D gravity model. Especially for the upper crustal blocks, the modelled densities together with seismic velocity information were interpreted in terms of plausible lithologies. Accordingly, we assigned lithology-dependent literature values (e.g. [31]) to those units, for which no direct measurements were available. Constant temperature values of 8°C at the surface and 1300°C at the LAB were assigned as boundary conditions.

The 3D thermal model was validated by 2240 corrected bottom-hole temperatures and undisturbed temperature logs from 217 wells [5].

Table 1. Rock Properties assumed for 3D gravity and thermal modelling (UC = upper crystalline crust).

Model Unit	Prevailing Lithology	Velocity [km/s]	Bulk Density [kg/m^3]	Thermal Conductivity (*: Matrix) [$W\ m^{-1}\ K^{-1}$]	Radiogenic Heat Production [$\mu W/m^3$]
Quaternary/Tertiary volcanics	Basalt [5]	/	2860 [5]	1.80 [5]	0.20 [31]
Quaternary/Tertiary sediments	Clayrich sandstone [32]	/	2050 (> -200 masl) 2240 (-200 to -2600 masl) 2440 (< -2600 masl)	1.80* [33]	1.00 [34]
Cretaceous	Carbonates [35]	/	2560 [30]	2.20 [30]	0.40 [31]
Muschelkalk/Keuper (Mid/Late-Triassic)	Carbonates [5]	/	2770 [28]	2.00 [5]	0.80 [34]
Buntsandstein (Early Triassic)	Sandstone [5]	/	2600	2.60 [5]	0.80 [34]
Zechstein (Late Permian)	Dolomite [5]	/	2540 [28]	2.30 [5]	0.80 [34]
Permo-Carboniferous	Sandstone [5], (basaltic) andesites [36]	/	2800	2.20 [5]	1.40 [37]
Rhenohercynian UC	Slate [5]	5.9 - 6.2 [21]	2710	2.71 [5]	1.00 [30]
Northern Phyllite Zone UC	Phyllite [5]	6.0 - 6.2 [21]	2710	2.70 [5]	3.00 [38]
Mid-German Crystalline High UC	Granitoids [10]	6.0 - 6.2 [21]	2720	2.40 [5]	1.80 [30]
Odenwald UC	Granitoids [10]		2670	3.00 [30]	1.80 [30]
Saxothuringian UC	Slate, granite [39]	5.8 - 6.2 [21]	2730	3.00 [39]	2.50 [39]
Lower crystalline crust	Unknown	6.5 - 7.0 [21]	2900	2.40 [40]	0.15 [31]
Lithospheric mantle	Peridotite	7.8 - 8.4 [21]	3300	3.95 [41]	0.03 [41]
Asthenospheric mantle	Peridotite	/	3300	/	/

3. Results

3.1. 3D Gravity Modelling

The main characteristics of the 3D structural and density model are illustrated in Figures 2 and 3. As the sedimentary successions, the depth of the Moho and the LAB were well constrained, we used 3D gravity modelling to evaluate the internal structure of the crystalline crust.

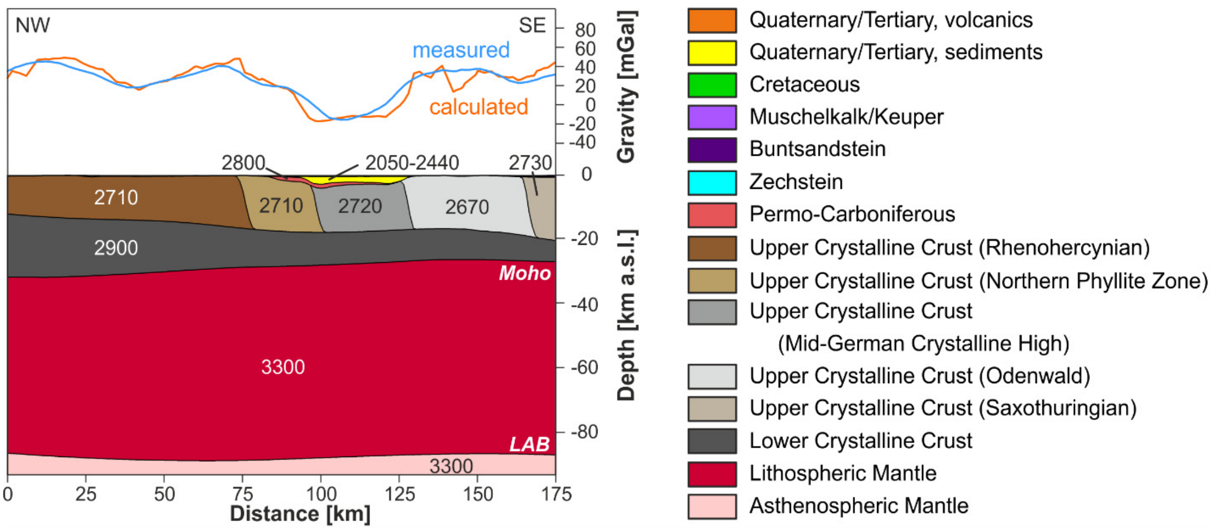

Fig. 2. NW-SE profile of the 3D structural model perpendicular to the Variscan domains illustrates some of the modelled sedimentary units, the heterogeneous upper crystalline crust, the lower crust and the lithospheric and asthenospheric mantle. Densities are given in kg/m^3. Above the calculated (orange) and measured (blue) gravity anomalies along the profile are displayed (see Fig. 3 for location of the profile).

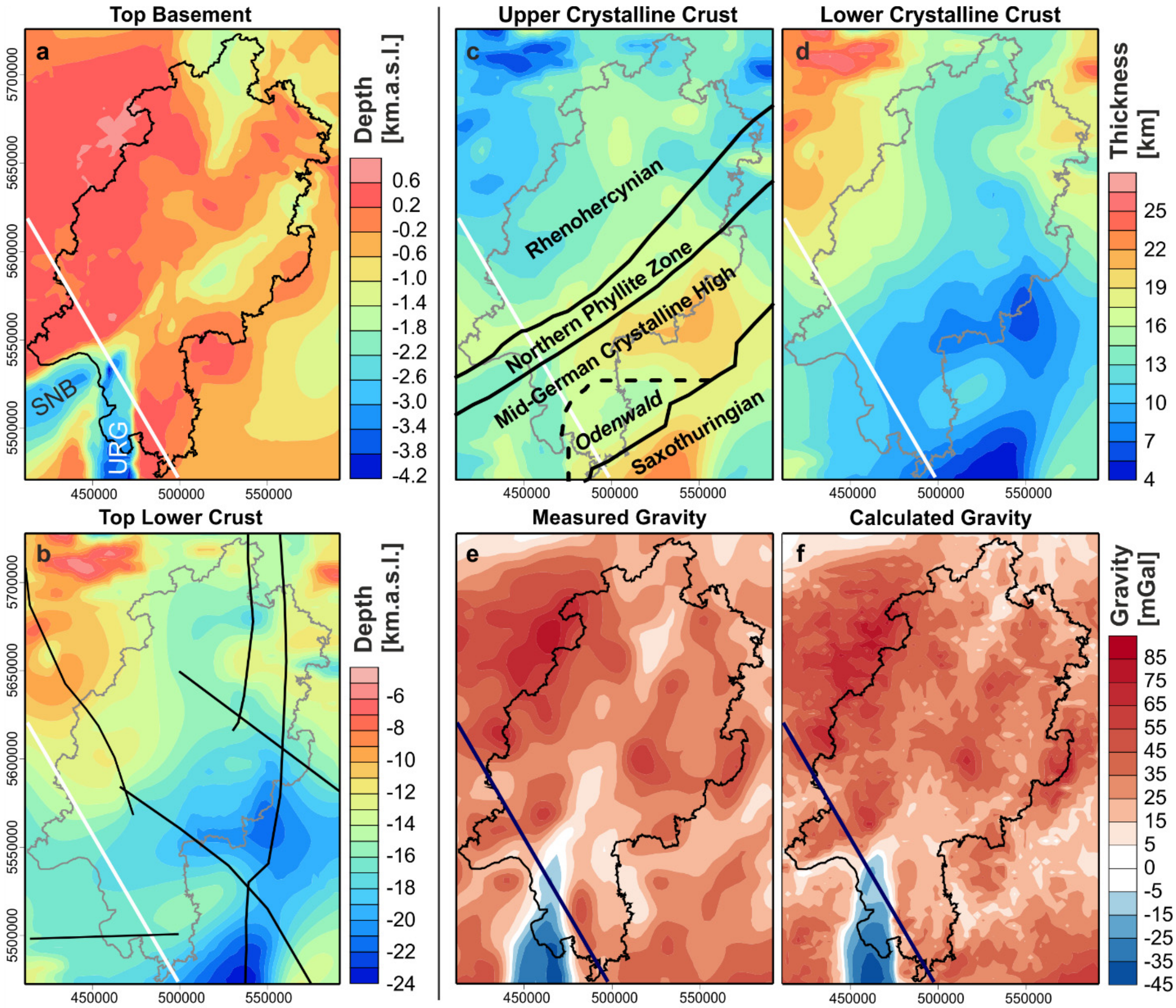

Fig. 3. (a) Map of top basement shows deep basement and therefore thick sediments or sedimentary rocks in the SW of the model area (SNB: Saar-Nahe Basin; URG: Upper Rhine Graben; cf. Fig. 1a). The black line shows the borders of the federal state of Hessen, the white line marks location of the profile (Fig. 2). (b) Depth of the top lower crust based on the seismic reflection and refraction profiles (black lines) and the 3D gravity modelling. (c) Seismic- and gravity-constrained thickness of the upper crystalline crust with differentiated bodies of homogeneous density that correspond to the Variscan domains (after Bär [5]). (d) Thickness of the lower crystalline crust. (e) Map of the measured [27] and (f) map of the calculated free-air gravity anomalies.

The modelled depth of the crystalline basement (Fig. 3a) varies by up to 5 km across the area. Red colours show areas of a shallow basement that crops out e.g. in the Rhenish Massif and the Odenwald. In contrast, blue colours indicate a relatively deep basement below the URG and the Saar-Nahe Basin. Both basins contain up to 4 km of sedimentary infill in the study area. The modelled depth of the top lower crust (Fig. 3b) is consistent with the available deep seismic profiles (Fig. 1c) and gravity and varies from a depth of -4 km in the NW to -24 km in the SE. Consequently, the upper crystalline crust (Fig. 3c) is rather thin in the NW and thicker in the SE, while the lower crystalline crust (Fig. 3d) shows the opposite pattern.

In detail, the upper crystalline crust was subdivided into 5 distinct bodies, four of them confined by the boundaries of the Variscan domains (Fig. 2, 3c). The borders between the Rhenohercynian, the Northern Phyllite Zone, the Mid-German Crystalline High and the Saxothuringian are represented by steep SE dipping boundaries from their surface outcrops to depth (Fig. 2). In addition to the Variscan domains, gravity modelling required a fifth body with a rather low density below the region of the Odenwald (Fig. 1a, 2, 3c).

In summary the lithosphere-scale density model that reproduced the first-order characteristics of the measured gravity anomaly best is characterised by 15 layers: Quaternary/Tertiary volcanics, Quaternary/Tertiary sediments, Cretaceous, Muschelkalk/Keuper, Buntsandstein, Zechstein, Permo-Carboniferous, upper crystalline crust (differentiated into Rhenohercynian, Northern Phyllite Zone, Mid-German Crystalline High, Odenwald and Saxothuringian), lower crystalline crust, lithospheric mantle and asthenospheric mantle.

The resulting gravity anomaly is mostly positive (Fig. 3e, f), with a maximum of 90 mGal in the area of the Rhenish Massif, mainly caused by the thick and shallow lower crystalline crust in this area (Fig. 3d). However, the URG is characterised by a pronounced negative anomaly of -45 mGal due to its thick infill of poorly consolidated Quaternary and Tertiary sediments (Fig. 3a; Tab. 1). In contrast, the thick infill of the Saar-Nahe Basin does not result in a negative gravity anomaly as it includes dense basaltic andesites and highly compacted Permo-Carboniferous sediments. Comparing the measured and calculated gravity anomalies, the difference widely is <10 mGal, but locally in the range of ±35 mGal.

3.2 3D Thermal Modelling

The 3D conductive thermal model, validated with 2240 corrected bottom hole temperature and undisturbed temperature log data from 217 wells ([5]; Fig. 1c), was calculated based on the gravity constrained 3D structural model. It predicts 79% of the measured temperature data with an accuracy of ±4°C (Fig. 4). Though the model shows a slightly too warm trend (Fig. 4a), Figure 4b illustrates a generally good fit between modelled and observed temperatures. Locally too-cold and too-warm temperatures mostly are found in the SE part of the model and follow the trend of the western boundary fault of the URG.

Overall, the 3D conductive thermal model predicts a subdivision into two parts. Colder temperatures are predicted for the NW of the study area while in the SE warmer temperatures prevail (Fig. 5a, b). At a depth of 1 km relatively high temperatures are predicted in the URG and the region of the Vogelsberg. Medium temperatures are found in the Saar-Nahe Basin and in the SE of the model area. In contrast, colder temperatures dominate in the centre of the southern part. The same trends are predicted at a depth of 10 km (Fig. 5b) though the pattern is smoother at larger depth.

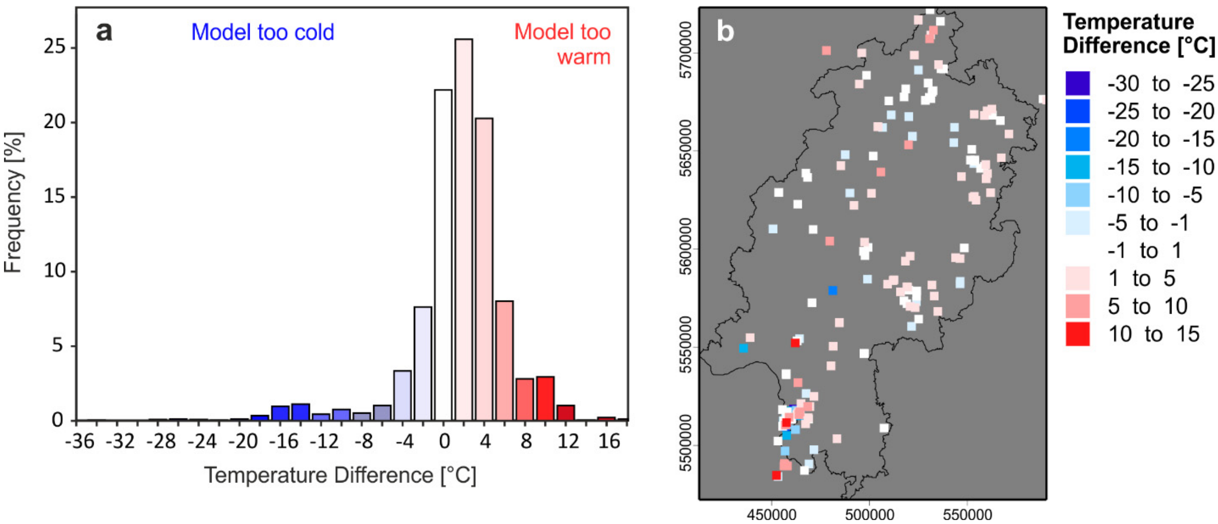

Fig. 4. (a) Histogram of all temperature differences indicating a slightly too warm trend in the modelled temperatures. (b) Local temperature differences determined by calculating modelled minus measured temperature (median values for wells with temperature logs).

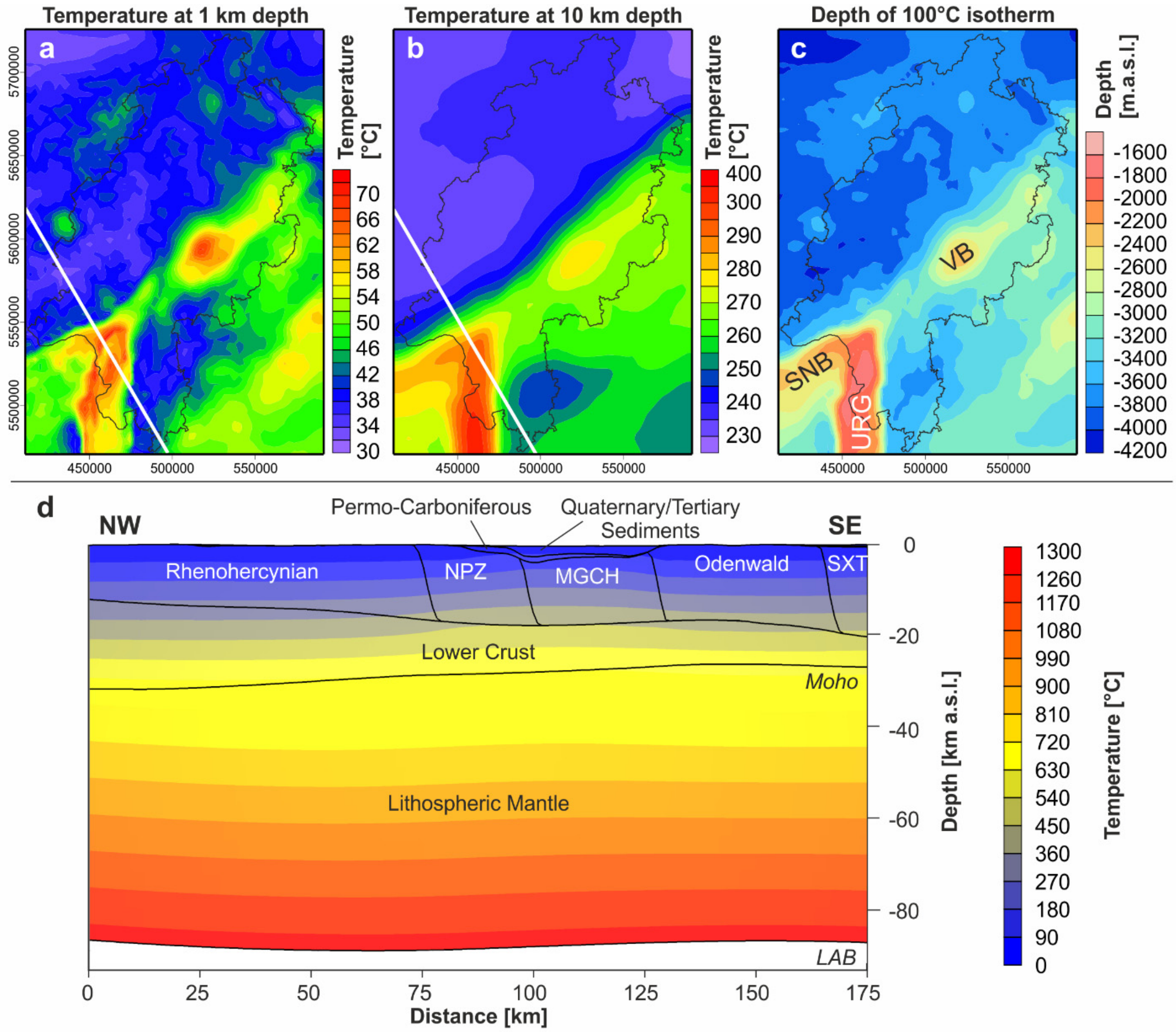

Fig. 5. (a) Temperatures at 1 km depth and (b) at 10 km depth. (c) Depth map of the 100°C-isotherm (VB: Vogelsberg). (d) NW-SE profile through the 3D thermal model with borders of the model units in black (profile corresponds to profile in Fig. 2, see Fig. 5a/b for location of the profile; NPZ: Northern Phyllite Zone, MGCH: Mid-German Crystalline High, SXT: Saxothuringian).

The 100°C isotherm (Fig. 5c) can be regarded as a target for geothermal exploration and the depth to this isotherm reflects the same trends as the temperature-depth maps. Especially in the URG the 100°C isotherm is found at relatively shallow depth of around -1600 masl. In contrast, the 100°C isotherm is much deeper in the NW of the model area where it may reach -4200 masl.

The same profile as in Figure 2 was chosen to illustrate how the thermal field changes with depth (Fig. 5d). While the isotherms in the deepest part of the model follow the structure of the LAB, this effect vanishes in the crustal part. Below the URG, the Northern Phyllite Zone and the Mid-German Crystalline High the isotherms are bent upward, which correlates with a higher geothermal gradient.

4. Discussion

The presented 3D structural model is the first lithospheric-scale model of Hessen, which differentiates sediments and sedimentary rocks, a heterogeneous crust and the lithospheric mantle. In addition, the model resolves 4 Variscan domains as well as one additional block in the upper crystalline crust not only in structure but also in lithology-dependent rock properties.

Our results indicate that the upper crust is characterised by a heterogeneous distribution of thermal properties whereas the density variations are less pronounced within the upper crust. Evidence for different lithologies of the Variscan domains are found mainly in outcrops. Measurements indicate for example that the Mid-German Crystalline High is characterised by a higher density (2740 kg/m³) than the Rhenohercynian and Northern Phyllite Zone (2630 kg/m³). However, our 3D gravity modelling indicates rather small density contrasts (Tab. 1; Fig. 2). The differences might be due to the weathering behaviour of the different lithologies, which influence the occurrence of outcrops and thus might result in a sampling bias. Only the upper crust of the Odenwald, where an abundance of felsic plutonic rocks are present, requires a remarkably lower density (2670 kg/m³) to fit the observed gravity. Without differentiation of the Odenwald, a local gravity residual of -40 mGal would be produced.

Our findings are almost consistent with previous 2D gravity studies [42, 43], which were performed along W-E cross sections through the URG. They show that the basement is differentiated into blocks with different densities. Although the basement blocks in these studies were not correlated with the Variscan domains, the location of the blocks and the assigned densities are similar to the ones of our model, showing at least the same trends. Gutscher [43] found densities of 2670-2720 kg/m³ below and west of the URG compared to 2720 kg/m³ of the Mid-German Crystalline High in our model. In the Odenwald he found lower density values of 2620-2670 kg/m³, which fits the 2670 kg/m³ in our model. Buness et al. [42] found exactly the same density of 2670 kg/m³ for the basement in the Odenwald. Although they assume only a density of 2620 kg/m³ for the crust below the URG, which can be easily explained by the higher degree of rift related faulting and fracturing, 2710 kg/m³ for the crust west of the Graben is similar to our 2720 kg/m³ assigned for the Mid-German Crystalline High.

Furthermore, our results indicate that simple subvertical boundaries between the Variscan domains are sufficient to achieve a fit between calculated and measured gravity. This is consistent with results of Franke et al. [17], Stets & Schäfer [9] and Martha et al. [44] that postulate steeply dipping Variscan units at least for most of the upper crust.

Like for the density model a differentiated distribution of thermal properties in the upper crust is required to fit the observed temperatures. The most striking result of the 3D conductive thermal model is the subdivision of the study area into a colder NW and a warmer SE part. The region of cold temperatures in the NW part of the model area (Fig. 5a, b) correlates with the location of the Rhenohercynian (Fig. 1a, 3c), which is the northernmost part of the Variscan belt und consists mainly of slates. The characterisation of this prevailing lithology is based on outcrop analogue studies in the Rhenish Massif, which is a large part of the outcropping crust in the northwestern model area (Fig. 1a, 3a).

As the sedimentary cover is very thin E of the Rhenish Massif and the thickness variations of the upper crust are small, radiogenic heat production is the main controlling factor of the shallow temperature field in the NW part of the study area. Compared to the other Variscan upper crustal units, the upper crust of the Rhenohercynian has a relatively low radiogenic heat production (Tab. 1). This explains the colder temperatures in the NW.

The southeastern part of the model area shows overall higher temperatures (Fig. 5a, b). This is caused by the much higher radiogenic heat production of the Northern Phyllite Zone, most parts of the Mid-German Crystalline High and the Saxothuringian crust. Assuming a homogeneous upper crystalline crust with the properties of the Rhenohercynian - the largest Variscan domain in our study area - the model would underestimate the measured temperature data in the southern part of the model. Similar results related to the influence of the crystalline crust on the thermal field have been proposed e.g. for the Central European Basin System [1] and North America [45].

However, local variations in the thermal field indicate the important effect of thermal blanketing by low-conductive sediments. The almost circular spot of higher temperatures in the central part of Hessen can be correlated to the location of the Vogelsberg (Fig 1a), which is a Tertiary volcanic structure, consisting mainly of basalt with comparably low thermal conductivity. The second area of comparably high temperatures is the URG in the SE part of the study area (Fig. 1a, 5a, 5b). Though characterised by different densities, the URG sediments and the Vogelsberg volcanics are thermally low-conductive in response either to their high porosities or to their mineralogy. Accordingly, these low-conductive units cause locally high temperatures at shallow depth below the URG and the Vogelsberg. This thermal blanketing effect is superimposed on the effect of the high radiogenic heat production of the Mid-German Crystalline High and the Northern Phyllite Zone (Fig. 5a). Comparing both areas of locally high temperatures, the thermal blanketing effect below the Vogelsberg is not as efficient as below the URG. At a depth of

1 km similar temperatures are predicted for both regions. However, as the insulating sediments of the Rhine Graben are much thicker than the Vogelsberg volcanics, the resulting temperatures are much higher at 10 km depth below the URG than below the Vogelsberg (Fig. 5b). The largest misfit between conductively modelled and observed temperatures along the western boundary fault of the URG indicates potential influences of advective heat transport.

The Permo-Carboniferous lithologies of the Saar-Nahe Basin, which has a similarly deep basement as the URG (Fig. 3a), are characterised by a higher thermal conductivity. This is related to their composition of volcanic and highly compacted sandstones that leads to the prediction of lower temperatures in the Saar-Nahe Basin compared to the URG.

In contrast, an area of cold temperatures is predicted in the centre of the southern model area (Fig. 5a, b), which correlates spatially with the location of the Odenwald crystalline crust. This can be explained by the high thermal conductivity of the granitoids of the Odenwald unit that crops out to the surface in a considerably large area. Without low-conductive sediments on top, this leads to cooling due to an efficient heat escape to the surface.

Despite large depth variation of the LAB (-74 km in the NW and -102 km in the E), the contrasts in radiogenic heat production (within the crystalline crust) and thermal conductivity (between sediments and crust) dominate the shallow thermal field (Fig 5d).

5. Conclusion

We conclude that the Variscan domains are characterised by different densities and thermal rock properties. In particular, the assumed variations in radiogenic heat production of the Variscan domains exert a strong control on the present-day shallow thermal field of Hessen. The predicted division of the temperature field in a colder NW and a warmer SE part is caused by the low radiogenic heat production of the Rhenohercynian compared to the other Variscan domains. In addition, insulating sediments of the URG and volcanics of the Vogelsberg cause locally higher temperatures due to thermal blanketing.

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References

[1] Scheck-Wenderoth M, Cacace M, Maystrenko YP, Cherubini Y, Noack V, Kaiser BO, Sippel J, Lewerenz B. Models of heat transport in the Central European Basin System: Effective mechanisms at different scales. Mar Pet Geol 2014; 55:315-331.

[2] Arndt D, Bär K, Fritsche J-G, Kracht M, Sass I, Hoppe A. 3D structural model of the Federal State of Hesse (Germany) for geopotential evaluation. Z Dtsch Ges Geowiss 2011; 162:353-369.

[3] Meissner R, Bortfeld RK. DEKORP-Atlas: Results of Deutsches Kontinentales Reflexionsseismisches Programm. Springer Verlag, Berlin Heidelberg; 1990.

[4] BGR. Gk1000 (Bundesanstalt für Geowissenschaften und Rohstoffe). 2014.

[5] Bär K. Untersuchung der tiefengeothermischen Potenziale von Hessen. PhD Thesis, TU Darmstadt; 2012.

[6] Ziegler PA. European Cenozoic rift system. Tectonophysics 1992; 208:91-111.

[7] Franke W. The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. Geol Soc London Spec Publ 2000; 179:35-61.

[8] Kossmat F. Gliederung des varistischen Gebirgsbaues. Abh. Sächsisches Geol. Landesamt 1927; 1:39.

[9] Stets J, Schäfer A. The Lower Devonian Rhenohercynian Rift - 20 Ma of sedimentation and tectonics (Rhenish Massif, W-Germany). Z Dtsch Ges Geowiss 2011; 162:93-115.

[10] Stein E. The geology of the Odenwald Crystalline Complex. Mineralogy and Petrology 2001; 72:7-28.

[11] Maystrenko YP, Scheck-Wenderoth M. 3D lithosphere-scale density model of the Central European Basin System and adjacent areas. Tectonophysics 2013; 601:53-77.

[12] Lützner H, Kowalczyk G. Stratigraphie von Deutschland X. – Rotliegend der variscischen Innenbecken. Schweizerbart, Stuttgart; 2012.

[13] StMWIT. Bayerischer Geothermieatlas (Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie München). 2010.

[14] Amante C, Eakins BW. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical

Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. 2009.
[15] Gabriel G, Vogel D, Scheibe R, Wonik T, Pucher R, Krawczyk C, Lindner H. Anomalien des erdmagnetischen Totalfeldes der Bundesrepublik Deutschland 1: 1.000.000 (LIAG, Hannover). 2010.
[16] Dekorp Research Group. The deep reflection seismic profiles DEKORP 3/MVE-90. Z Geol Wiss 1994; 22:623-825.
[17] Franke W, Bortfeld RK, Brix M, Drozdzewski G, Dürbaum HJ, Giese P, Janoth W, Jödicke H, Reichert C, Scherp A, Schmoll J, Thomas R, Thünker M, Weber K, Wiesner MG, Wong HK. Crustal structure of the Rhenish Massif: results of deep seismic reflection lines DEKORP 2-North and 2-North-Q. Geol Rundsch 1990; 79:523-566.
[18] Oncken O. Orogenic mass transfer and reflection seismic patterns - evidence from DEKORP sections across the European Variscides (central Germany). Tectonophysics 1998; 286:47-61.
[19] Oncken O, von Winterfeld C, Dittmar U. Accretion of a rifted passive margin: The Late Paleozoic Rhenohercynian fold and thrust belt (Middle European Variscides). Tectonics 1999; 18:75-91.
[20] Schwarz M, Henk A. Evolution and structure of the Upper Rhine Graben: insights from three-dimensional thermomechanical modelling. Int J Earth Sci 2005; 94:732-750.
[21] Blundell D, Freeman R, Mueller S. A continent revealed: The European Geotraverse. Cambridge University Press; 1992.
[22] Barton PJ. The relationship between seismic velocity and density in the continental crust - a useful constraint? Geophys J Int 1986; 87:195-208.
[23] Christensen NI, Mooney WD. Seismic velocity structure and composition of the continental crust: A global view. J Geophys Res 1995; 100:9761-9788.
[24] Mechie J. A 3-D, P-wave velocity, crustal structure model for Germany derived from seismic refraction / wide-angle reflection data. in: 67th Annual Meeting of the German Geophysical Society (DGG), Aachen, Germany; 2007.
[25] Geissler WH, Sodoudi F, Kind R. Thickness of the central and eastern European lithosphere as seen by S receiver functions. Geophys J Int 2010; 181:604-634.
[26] Götze HJ, Schmidt S. IGMAS+ a new 3D gravity, FTG and magnetic modelling software tool. In: Lane RJL (ed) Airborne Gravity 2010. in: Abstracts from the ASEG-PESA airborne gravity 2010 workshop: published jointly by Geoscience Australia and the Geological Survey of New South Wales, Geoscience Australia Record 2010/23 and GSNSW File GS2010/0457; 2010.
[27] Pavlis NK, Holmes SA, Kenyon SC, Factor JK. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). J Geophys Res [Solid Earth] 2012; 117:B04406.
[28] Meixner J, Schill E, Gaucher E, Kohl T. Inferring the in situ stress regime in deep sediments: an example from the Bruchsal geothermal site. Geothermal Energy 2014; 2:1-17.
[29] Bayer U, Scheck M, Koehler M. Modeling of the 3D thermal field in the northeast German basin. Geol Rundsch 1997; 86:241-251.
[30] Haenel R. Geothermal Investigations in the Rhenish Massif. in: Fuchs K, Von Gehlen K, Mälzer H, Murawski H, Semmel A (Eds.) Plateau Uplift: The Rhenish Shield - A Case History. Springer Verlag Berlin, Heidelberg, New York, Tokyo; 1983. pp. 228-246.
[31] Vilà M, Fernández M, Jiménez-Munt I. Radiogenic heat production variability of some common lithological groups and its significance to lithospheric thermal modeling. Tectonophysics 2010; 490:152-164.
[32] Grimm KI. Stratigraphie von Deutschland IX - Tertiär, Teil 1: Oberrheingraben und benachbarte Tertiärgebiete. Schweizerbart, Stuttgart; 2011.
[33] Midttømme K, Roaldset E. Thermal conductivity of sedimentary rocks: uncertainties in measurement and modelling. Geol Soc London Spec Publ 1999; 158:45-60.
[34] Clauser C, Villinger H. Analysis of conductive and convective heat transfer in a sedimentary basin, demonstrated for the Rheingraben. Geophys J Int 1990; 100:393-414.
[35] Kaever M, Lommerzheim A. Die Bohrung Metelen 1001 Stratigraphie, Palökologie und Fazies zyklischer Sedimente des Campans im nordwestlichen Münsterland (NW-Deutschland). Facies 1991; 24:267-284.
[36] Schäfer A. Tectonics and sedimentation in the continental strike-slip Saar-Nahe Basin (Carboniferous-Permian, West Germany). Z Dtsch Ges Geowiss 2011; 162:127-155.
[37] Cacace M, Scheck-Wenderoth M. Modeling the Thermal Field and the Impact of Salt Structures in the North East German Basin. in: Proceedings World Geothermal Congress 2010, Bali, Indonesia; 2010. pp. 1-8.
[38] Čermák V, Rybach L. Thermal Properties. in: Landolt-Börnstein: Zahlenwerte und Funktionen aus Naturwissenschaften und Technik. Band 1: Physikalische Eigenschaften der Gesteine. Springer-Verlag, Berlin, Heidelberg, New York; 1982. pp. 305-371.
[39] Berger H-J, Felix M, Görne S, Koch E, Krentz O, Förster A, Förster H-J, Konietzky H, Lunow C, Walter K, Schütz H, Stanek K, Wagner S. Tiefengeothermie Sachsen. Schriftenreihe des LfULG 2011; 9:1-108.
[40] Sippel J, Fuchs S, Cacace M, Braatz A, Kastner O, Huenges E, Scheck-Wenderoth M. Deep 3D thermal modelling for the city of Berlin (Germany). Environ Earth Sci 2013; 70:3545-3566.
[41] Scheck-Wenderoth M, Maystrenko YP. Deep Control on Shallow Heat in Sedimentary Basins. Energy Procedia 2013; 40:266-275.
[42] Buness H, Gabriel G, Ellwanger D. The Heidelberg Basin drilling project: Geophysical pre-site surveys. Quaternary Science Journal 2008; 57:338-366.
[43] Gutscher M-A. Gravity interpretation along seismic reflection profile DEKORP 9-N (northern Rhine Graben). Terra Nova 1991; 3:166-174.
[44] Martha SO, Zulauf G, Dörr W, Nesbor H-D, Petschick R, Prinz-Grimm P, Gerdes A. The Saxothuringian-Rhenohercynian boundary underneath the Vogelsberg volcanic field: evidence from basement xenoliths and U-Pb zircon data of trachyte. Z Dtsch Ges Geowiss 2014; 165:373-394.
[45] Mareschal JC, Jaupart C. Variations of surface heat flow and lithospheric thermal structure beneath the North American craton. Earth Planet Sci Lett 2004; 223:65-77.